Micro-channel plate based X-ray optics

M. Beijersbergen^{a,1}, M. Bavdaz^a, A. Peacock^a, E. Tomaselli^b, G. Fraser^c, A. Brunton^c, E. Flyckt^d, M. Krumrey^e, and A. Souvorov^f

^aSpace Science Department of ESA, ESTEC, 2200 AG Noordwijk, Netherlands

^bTechnical and Operational Support Department of ESA, ESTEC, 2200 AG Noordwijk, Netherlands

^cSpace Research Centre, Leicester University, Univ. Rd., Leicester LE1 7RH, UK

^dPhotonis, Av. R. Roncier, 19106 Brive la Gaillarde, France

^ePhysikalisch-Technische Bundesanstalt, Abbestr. 2-12, D-10587 Berlin, Germany

^fEuropean Synchrotron Radiation Facility, B.P. 220, F-38043 Grenoble, France

ABSTRACT

X-ray optics based on micro-channel plates (MCPs) offer some distinctive advantages over conventional technologies used to produce imaging optics for astrophysics applications. Such micro-pore optics (MPOs) are far lighter and allow a larger stacking density than optics based on metallic foils or plates. Until recently, X-ray optics based on MCPs were not feasible or useful because of the limited quality of the MCPs.

We have produced thick square pore MPOs of improved quality and have developed methods to stack the channels in a radial pattern, as required for imaging optics based on Wolter type I or II designs. The individual plates were tested in synchrotron radiation facilities and conventional beam lines to determine their geometric and surface scattering properties.

Keywords: X-ray optics, Micro-channel plates, X-ray astrophysics, X-ray telescopes

1. INTRODUCTION

Imaging X-ray optics have traditionally suffered from the fact that small grazing angles are required to get a sufficiently high reflectivity. At higher energies the angles have to be so small (4' at 30 keV) that most of the aperture is blocked by the thickness of the reflecting surfaces. This leads to massive optics with a low efficiency with respect to aperture utility. Furthermore the stacking or nesting and alignment of the reflecting surfaces is a complex and expensive procedure. The production of heavily nested X-ray telescopes with an appreciable collecting area such as XMM is therefore complex and expensive, and this situation only becomes more severe at higher X-ray energies. If it were possible to produce very thin reflecting surfaces that are already packed with the appropriate geometry, then this opens the door to light-weight optics that can be made to function efficiently at higher energies [1].

The technology used to produce micro-channel plates offers this possibility. Micro-channel plates are typically made by drawing glass fibers consisting of a core and cladding of different glass types. These fibers are stacked in a regular pattern and then this stack is drawn into a fiber again, producing a so-called multifiber. This process can be repeated several times. After finally stacking the multifibers into a block, typically a few centimeters long, plates can be cut and polished. From a single block an appreciable number of plates of a few mm thickness can be cut. The cores of the fibers are etched away so that a glass plate is obtained with a large number of parallel holes. With current-day technology plates of 170x60x2 mm can be produced with holes of about 6 micron diameter on a grid with a pitch of 8 micron.

The key technology to produce imaging X-ray optics with based on MCPs is to be able to produce holes that have walls with such characteristics that they efficiently reflect X-rays towards a single focus. This can be achieved with MCPs having square holes, that is with 4 flat walls. Naturally the surface roughness of the walls has to be sufficiently low to be able to reflect the X-rays.

A geometry that is close to the existing method of producing micro-channel plates is the Lobster eye optic, which consists of square pores stacked in a square packing arrangement (Fig. 1a). If the plate is not deformed, such that the channels are perfectly parallel, such a configuration can be used to focus in a confocal arrangement. If the plate is curved however into a

¹ mbeijers@estec.esa.nl

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spherical shape the optic can be used to focus X-rays from a source at an infinite distance. The image however has the shape of a crucifix. Two orthogonal lines are produced by reflections from the sidewalls, whereas only rays that are reflected from two orthogonal walls are brought to the true focus. Recently first results have been obtained with such an optic [2]. This optic had a moderate image quality clearly limited by the imperfections of the plate and a moderate aspect ratio (channel length over channel diameter) of 100 which limits the high-energy response.

In this paper we describe results from a new generation of imaging X-ray optics based on micro-channel plate technology. We have produced fibers and multifibers with an aspect ratio of 500 that have a low surface roughness and good imaging properties. From these we have produced Lobster eye optics with a good imaging quality. We have also produced the first prototypes of plates with a radial instead of square packing geometry, which will eventually lead to true imaging optics in a Wolter-I geometry.

Even though our main interest is to use this kind of X-ray optics for astronomy, it is obvious that there is an enormous potential for application of this kind of optics in other fields using X-ray imaging (fluorescence microscopy, medical imaging, X-ray microscopy, X-ray lithography, X-ray fluorescent planetary remote sensing etc).

2. MICROCHANNEL PLATES

Micro-channel plate optics in the two different geometries sketched in Fig. 1 have been produced by Photonis (Fr). The process starts with a boule that consists of a bar of glass of 10x10x100 cm, which will form the core. The walls of the bar are polished and parallel to the opposite wall and orthogonal to the adjacent walls within 0.1 deg. A square bar with a square hole made from a different type of glass forms the cladding into which the core fits. This boule is fed into a drawing tower that pulls it into a fiber of 0.5x0.5 mm with square profile. This fiber is cut into pieces of 60 cm length which are stacked manually into a square arrangement of 55x55 fibers. This pack is cemented and passed through the drawing tower again, which leads to multifibers with a diameter of 0.66x0.66 mm, containing 55x55 fibers of 12x12 micron.

These multifibers have been stacked in the geometries shown in Fig. 1 with sizes of ~50x50x60 mm. The multifibers have been fused thermally under pressure after which the block becomes solid. Plates of 2 and 5 mm thickness have been cut from these blocks and the surfaces have been polished. Then the core glass has been etched in an HNO_3 solution over a period of several days. The result is a plate that contains millions of square holes running parallel between the two polished surfaces of the plate.

Figure 1: the layout of the micro-channel plate optics in a) square packing and b) radial packing.

3. SQUARE PACKED (LOBSTER EYE) OPTICS

Fig. 2 shows a microscope image of the fibers in the square packed plates. No significant deviation from orthogonality between the walls of the fiber or rounding of the surfaces could be observed in this image or electron microscope images of a fiber inside a multifiber (Fig. 2a). The image of the corner between four multifibers shows that one to two rows of fibers are distorted close to such an edge (Fig. 2b).

Figure 2: Nomarski microscope images of the fibers a) inside a multifiber and b) on the corner between four multifibers; c) electron microscope image of the square pores

We have tested these plates in the synchrotron radiation facilities of the Physikalisch-Technische Bundesanstalt (4 crystal monochromator beam line at Bessy II, Berlin, Germany) and of the European Synchrotron Radiation Facility (BM5 optics beam line at ESRF, Fr), as well as in a conventional X-ray source beam line at the Space Research Center (Leicester University, Leicester, UK). In the synchrotron facilities we were able to measure the reflection from an individual fiber to a multifiber up to a strip of 4x50 multifibers. In the conventional beam line we could measure the image quality under full illumination in a confocal arrangement.

By tilting the plate over an angle up to 0.1 degrees the transmitted beam as well as the beam reflected from the walls of the fibers could be observed. Figure 3 shows the superimposed image of the four reflections from the four different walls of a single fiber. The slope errors of the walls in the direction perpendicular to the incident beam is small, as shown by the narrow reflected stripes. The four walls clearly differ in the distribution of slope errors of the walls in the direction parallel to the incident beam, shown by the length of the reflected stripes. The image quality of one of the four walls of the fibers is better than 20 arcsec (cf. the XMM telescopes have a HEW of about 16 arcsec). The difference in spatial distribution

between the four walls of a single fiber appears to be reproduced amongst all the fibers even though the orientation of the fibers is randomized during stacking. This peculiar effect has thus far not been explained.

Figure 3: the reflections of the four side walls of an individual fiber, obtained by tilting the plate slightly in four different directions and superimposing the images. The central spot is that part of the direct beam that is not reflected by the plate because it was not tilted enough to block the beam. The images were taken with 10 keV radiation at the PTB beam line at Bessy.

A measurement of the size of the reflected spot as a function of the size of the incident beam showed that the alignment of the fibers in the multifiber bundle is good enough such that the performance of individual fibers dominate the image quality. Over the complete plate however, large-scale distortions cause a different alignment of the multifibers throughout the plate, which is the limiting factor to the image quality of the plate. An image quality of better than 6 arcmin has been obtained in full illumination (40x40 mm) (Fig. 4) which is so far the best resolution obtained with this kind of optics.

Figure 4: the crucifix image produced by a micro-channel plate optic with square packing in a confocal arrangement. The half-energy width of the spot is about 6 arcmin. Data taken at the beam line of the Space Research Centre of Leicester University at 1 keV.

The reflected and transmitted intensity has been measured as a function of energy between 2 and 30 keV at PTB Bessy and ESRF. Based on the Debye-Waller factor for the scattering losses, it can be concluded from the reflection coefficient at 10 keV that the RMS surface roughness of the walls is less than 15 Angstrom. This has been confirmed by an in-situ metrology measurement of the surface roughness inside the pores, which indicates an RMS surface roughness of between 5 and 15 Angstrom.

4. RADIAL MICRO-CHANNEL PLATE OPTICS

The crucifix image from a square pack optic limits the image quality severely. This problem can be overcome by using the radially packed geometry of Fig. 1b. With a single radially packed plate however the imaging quality is perfect for an on-axis source, but extreme coma occurs for an off-axis source. The solution to this is to use two plates in tandem, each with a different radius of curvature, such that an approximation to a Wolter-I geometry is obtained [3]. The imaging quality will now be limited by the size of the multifibers which are still square packed, the imperfections of the fiber and multifibers and the alignment quality of the radial stacking.

We have produced a first prototype of a radially packaged plate. The plate has been built up from the same multifibers as the square pack multifibers described in the previous section, but this time the multifibers are stacked in circles around a solid core cylinder of 5 mm diameter. Fig. 5 shows an image of this plate. Note the open areas between the multifibers caused by circular packing of square multifibers. This packing also causes more distortions of the multifibers at the corners where they touch the other multifibers.

Figure 6: a microscope image of the first radially packed micro-channel plate optic.

One of these plates has been tested using a strip beam (2x30 mm) at ESRF. The reflections from the fibers produce a spot in the center (behind the solid core cylinder) that has a half-energy width of 2 arcmin (Fig. 6). Around this spot the transmission through the square pores as well as through the holes between the multifibers are visible, together with the X-rays from multiple reflections in the pores. The plate has been scanned by rotating it around the optical axis such that different strips on the plate are illuminated. This results in similar images for all positions on the plate, but only after adjusting the orientation of the plate. This leads to the conclusion that the multifibers and their stacking is good enough to produce an image quality of about 2 arcmin. In this prototype plate the image quality is therefore limited by large-scale distortions of the plates.

Figure 6: Transmitted and reflected photons from a radially packed micro-channel plate optic using a 10 keV beam that illuminates an area of 2x30 mm. The central spot is the focus of the plate, the small bright spots around it are caused by transmission through the holes between the multifibers, and the two bright spots at the left and right hand side are caused by double reflections in a channel. Image taken at ESRF, Grenoble.

5. CONCLUSION

We have produced X-ray optics using micro-channel plate technology with square pores with an RMS surface roughness of less than 15 Angstrom and slope errors that systematically result in a half-energy width of less than 20 arcsec on some of the reflecting walls. The alignment of the fibers in the fiber bundles is good enough to maintain the quality; the limiting factor is currently the alignment of the fiber bundles in the plates.

We have produced radially packed micro-channel plate optics which retain most of the good imaging qualities of the fibers and fiber bundles of the square pack plates. Again the final image quality will be limited by the alignment of the fiber bundles in the plates.

These results open the door to light-weight, high-quality X-ray optics. If the multifiber alignment can be improved this technology could lead to X-ray imaging optics that have an imaging quality of 30 arcsec or better at a fraction of the weight of mirror shell technology such as that used in the XMM telescope.

Further improvement of the large-scale alignment should however be possible without drastic improvement in the micro-channel plate technology, by assembling smaller sections of the micro-channel plates under alignment control. This could for example be done by gluing small square sections by hand into a frame, while maintaining alignment with a simple optical alignment system.

An important technological step however is to be able to slump these plates into the correct spherical shape such that a focussing element is obtained that can be used to focus X-rays from infinity. We are currently developing the technology for this.

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